HOW MUCH GROUNDWATER DOES SOUTH AFRICA HAVE?

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ABSTRACT

This is a question that, until recently, hydrogeologists could not answer, much to the frustration of engineers and planners, not to mention hydrogeologists themselves. In 1998, Baron, Seward and Seymour built on the national hydrogeological mapping work of Vegter (1995) to produce a Harvest Potential (HP) Map of South Africa. Their estimate was 19 x 10^9 m^3/a. Haupt (2001) took this map a step further by recognizing that aquifer transmissivity is the main limiting factor in determining so-called harvest potential and came up with an estimate of groundwater availability of 10 x 10^9 m^3/a.

In late 2003, the Department of Water Affairs and Forestry (DWAF) initiated the Groundwater Phase 2 Project, which is aimed at the quantification of the groundwater resources of South Africa on a national scale. The project has been carried out by a consortium of consultants comprising SRK Consulting, GEOSS, WSM and CSIR (SGWC) in close collaboration with key DWAF personnel and was completed in June 2005. Algorithms have been developed for the estimation of storage, recharge, baseflow and the Reserve. The figures derived for the key aspects of recharge, storage and extractable groundwater are 30.52, 235.5 and $19x10^9m^3/a$, respectively.

Keywords: Groundwater; Quantification; Storage; Potential, Recharge

1. INTRODUCTION

South Africa is a relatively dry country. Its average rainfall of ~497 mm/a compares unfavourably with the world average of ~860mm/a. Twenty one percent of the country receives <200mm/a, qualifying it to be classed as desert. However the names of many towns reflect the dependence of the early settlers on groundwater and its importance in the establishment and spread of settlements. Names such as De Aar (the vein, an underground water source), Springs, the Fountains at Pretoria and the many towns ending with “fontein” testify to the importance of groundwater and its importance in the development of South Africa.

However, coupled with a low average rainfall and skewed distribution, <150mm in the arid north-west to >2000mm in the south-west and east coast areas, the geology of the country largely precludes the development of regional scale highly productive aquifers. More than 90% of the country is underlain by indurated sedimentary and crystalline basement rocks with little or no primary porosity. Highly permeable zones can be developed in fracture zones but it follows from the limited porosity and low rainfall over much of the country that long-term sustainable borehole yields are mostly low. Despite this somewhat gloomy prologue, groundwater plays a very important role in water supply to domestic, industrial, agricultural and mining users.

This paper mainly highlights and summarizes the findings of Sub-tasks 1, 2 and 3 of the Groundwater Resources Assessment Phase 2 (GRA2), i.e. quantification of storage, sustainable abstraction and recharge. Credit for the actual data evaluation, manipulation and development of algorithms is due to the key (SGWC Consortium) team members Alan Woodford, Julian Conrad, Ricky Murray, Karim Sami, Carel Haupt and Christine Colvin. Section 5 is based on their work.

2. PREVIOUS WORK

The many publications used as source material for this paper are listed in the References section. However, a few stand out as being the main sources and main works on the subject of groundwater quantification and availability. These are, in chronological order:

Vegter, JR (1995), An Explanation of a set of National Groundwater Maps.

This was the first attempt of a synoptic and visual representation of South Africa’s groundwater resources. It consists of an explanation booklet and a set of seven maps on two A0 sheets. These depict borehole prospects, saturated indices, mean annual recharge, groundwater component of river flow, depth to groundwater level, groundwater quality and hydrochemical types. The main maps basically represent a statistical analysis of information stored in the National Groundwater Data Base.

Baron, Seward and Seymour (1998). The Groundwater Harvest Potential Map of the Republic of South Africa.

This work covers the Harvest Potential Map published by the DWAF in 1996 and the subsequent report explaining the methodology followed.

DWAF (2001). Water Situation Assessment Model. Groundwater Resources of South Africa (Haupt, C)

This work represents a modification and update of the Harvest Potential Map to develop an overview of the groundwater resources of South Africa at a quaternary catchment level.

DWAF (1995-2003). Groundwater Resource Assessment Phase 1

Production of a set of 21 hydrogeological maps covering the country at a scale of 1:500 000, with accompanying explanatory booklets.

DWAF (2003-2005). Groundwater Resource Assessment Phase 2.

The first five projects are active under this portfolio. The main ones contributing to this paper are Project 1: Groundwater Quantification, Project 2: Planning Potential and Project 3a: Recharge. A separate paper is being presented at the Conference on this project by Jan Girman, the Portfolio Coordinator.

Water Research Commission (2004-2007). WR2005

This is the fourth iteration of the Surface Water Resources of South Africa but for the first time is following an integrated approach to include groundwater. The groundwater component has drawn heavily on the database and outputs from the GRA 2 project.

3. GROUNDWATER USE

To put the quantification of groundwater resources into perspective, a brief discussion on its use in South Africa is given.

Groundwater is widely but variably used across the whole of the country. Basson (1997) provides an overview of groundwater use for municipal schemes in towns with a population of >2500 and for irrigation. This is shown in Figure 1.

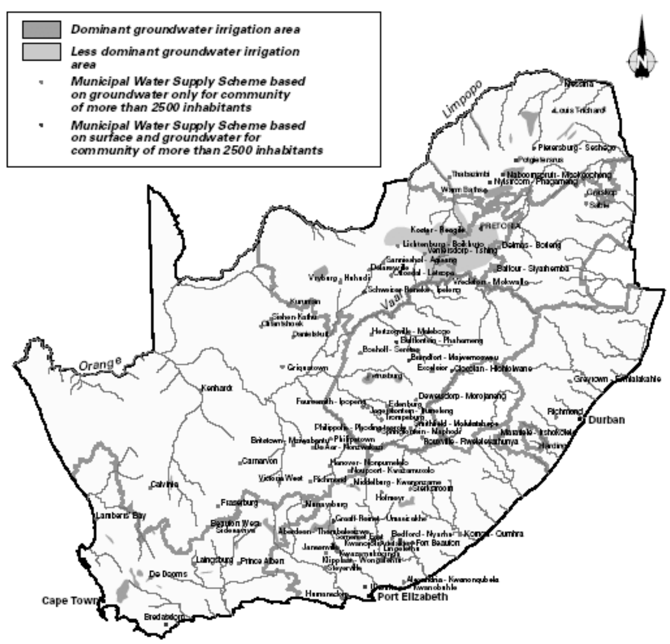

Figure 1: Groundwater exploitation in South Africa (Basson et al, 1997) <u>(not to scale)</u>
A more detailed breakdown of sectoral use by groundwater in the major catchments is provided by Hughes et all (2004) and is reproduced in Figure 2.

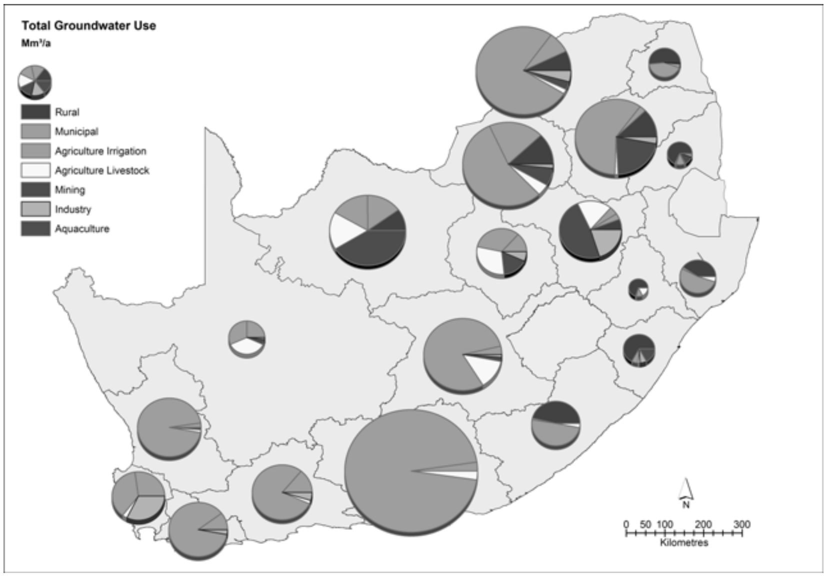

Figure 2: Summary of Sectoral WMA Groundwater Use

Hughes et al (2004) provide the most up to date estimate of total groundwater use in the country, deriving a figure of 1770 Mm^3/a. Sixty four percent of this is used for irrigation.

4. AVAILABILITY OF GROUNDWATER

Some of the most favourable areas/ aquifers regarding groundwater availability include:

- Dolomites of the West and Far West Rand. Deep leaching and cavern development gives rise to some of the highest yielding boreholes in the country (up to 100 ℓ/s).

- Table Mountain Group Aquifers of the Western and Eastern Cape. Tectonic forces and the brittle nature of the main sandstone formations has given rise to a well developed network of fractures, some extending to thousands of metres in depth (evidence from temperatures of up to 64^0C from hot springs such as Brandvlei). Coupled with some of the highest rainfall in the country, this has given rise to one of the most important aquifers in the country. Sustainable borehole yields of >10 ℓ/s are common.

- Coastal sand aquifers in the Western and Eastern Cape and northern Kwazulu-Natal. The town of Atlantis just north of Cape Town is supplied by ~3.5 Mm^3/a from this aquifer.

Other high yielding aquifers include basement granites in the Pietersberg-Dendron-Coetzerdam area, alluvial deposits along sections of major rivers such as the Limpopo and parts of the Karoo Sequence associated with dolerite dykes and ring structures.

The first attempt to provide a synoptic and visual representation of the groundwater resources of South Africa was that of Vegter (1995). The borehole prospects, saturated indices and recharge maps that he produced, in particular, provided a valuable indication of regional scale availability of groundwater.

This work was built-on by Baron, Seward and Seymour (1998) with production of the Groundwater Harvest Potential Map. Harvest Potential was defined by the authors as 'the maximum volume of groundwater that may be abstracted per annum without depleting aquifer'. This map is reproduced as Figure 3 below.

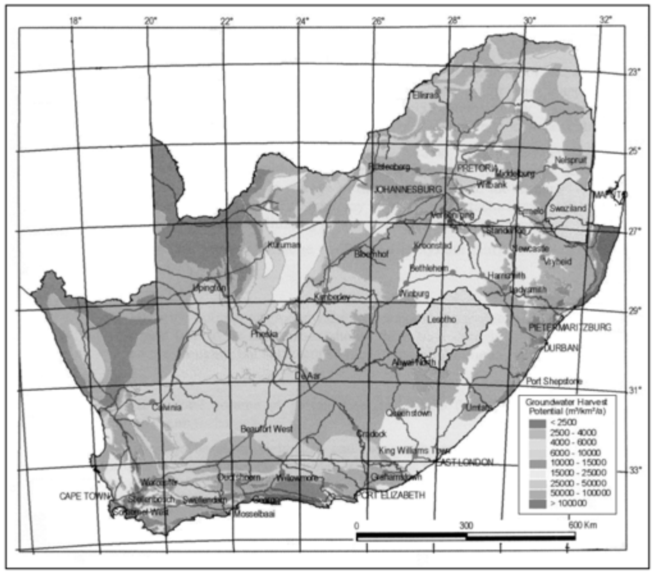

Figure 3: Groundwater Harvest Potential of SA (Baron et al, 1998)

The total Harvest Potential for the country was estimated at 19 x 10^9 m^3/a. This was qualified by the authors with the riders that this included base-flow contribution to rivers and that 'abstractability' of the resource was not taken into account. This figure of 19 x 10^9 m^3/a, although available in theory, could thus be significantly less in practice.

Haupt recognised that the main contributing factor limiting abstraction of available groundwater is transmissivity of the aquifer systems (Haupt, 2001). There is no regional information available on this aquifer property and so he carried out a qualitative evaluation using the relationship between borehole yield and transmissivitiy. He multiplied the Harvest Potential for each quaternary catchment by an exploitation factor (0.3 to 0.7) allocated to five average borehole yield categories. This gave a figure of ~10 x 10^9 m^3/a for Exploitation Potential. His Exploitation Potential Map is shown in Figure 4.

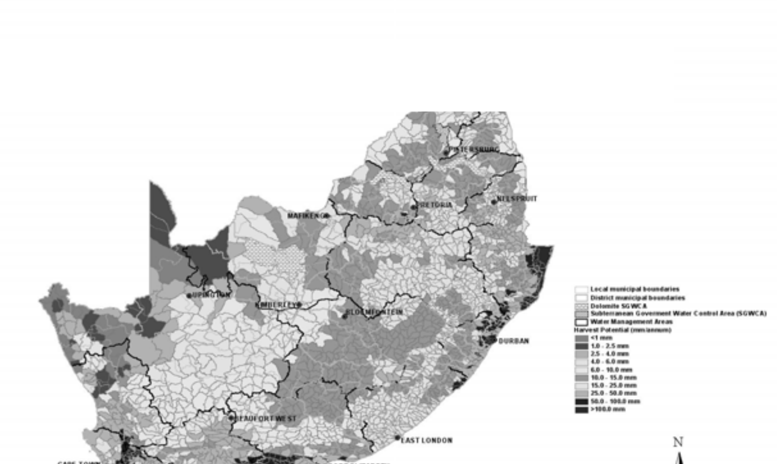

Figure 4: Exploitation Potential Map <u>(not to scale-ignore scale bar)</u>

5. QUANTIFICATION OF GROUNDWATER RESOURCES

While the Surface Water Resources of South Africa publication is in its fourth iteration, no similar such body of work is available for groundwater. The early attempts at quantifying the groundwater resources of South Africa, eg Enslin 1970, Vegter 1980, were largely educated guesses and not based on algorithms. The figures for sustainable groundwater yield derived by these pioneers of hydrogeology in the country were 2.5 x 10^9 m^3/a and 5.4 x 10^9 m^3/a, respectively.

In late 2003 the DWAF initiated the Phase 2 Groundwater Resources Assessment project, the main aim of which is to quantify South Africa's groundwater resources. The project comprises five sub-tasks, namely 1) Quantification (basically of aquifer storage), 2) Planning Potential Map (updated HP map), 3a) Recharge, 3b) Groundwater/Surface Water Interaction; 4) Aquifer Classification and 5) Groundwater Use.

Storage

The process of quantifying the groundwater resources of South Africa followed the steps outlined in Table 1.

Table 1: Process for Groundwater Resource Assessment and Allocation

Step	Task	Project No
1	Establish the volume of groundwater held in storage in the aquifer system. This involves defining various aquifer levels such as the thickness of the aquifer system.	1
2	Establish the rate of aquifer replenished from rainfall and the proportion of groundwater that can feasibly be abstracted, whilst taking into account the effects of droughts.	2 with input from 3
3	Establish the proportion of 2 above that should remain behind in the aquifer system in order to meet specific management criteria (e.g. the Reserve, prevention of land subsidence, maintain water quality in the aquifer, etc)	4 and Reserve Estimates
4	Establish the current abstraction	5
5	Establish the 'surplus' groundwater resources that can be allocated for further use.	-

A considerable portion of the work carried out during this project has been on developing the default values for verification of the methodology on a national scale where it was decided to generate inputs and outputs at a spatial resolution of 1km by 1km (1 km^2). Raster-based GIS layers or Grids were developed for various levels within a conceptual aquifer system. These aquifer levels are grouped into two broad zones; namely (i) 'static' storage zone, which is the volume of groundwater available in the permeable portion of the aquifer below the zone of natural water level fluctuation (level 2), and (ii) 'dynamic' storage zone, which is the volume of groundwater available in the zone of natural water level fluctuation. The levels are listed below:

Static storage
- Level 1 - base of the aquifer
- Level 2 - base of the natural dynamic groundwater elevation

Dynamic storage
- Level 3 - current groundwater elevation
- Level 4 - average groundwater elevation
- Level 5 - top of the aquifer

A sixth level (Management Waterlevel Restriction) was introduced to take into account environmental, legal or other constraints placed on the volumes of water that may safely be abstracted from an aquifer system, e.g. restrictions to ensure that DWAF 'Reserve' requirements are met, restrictions on maximum waterlevel drawdown in dolomitic aquifers due to the hazard of sinkhole formation or avoiding intrusion of saline water.

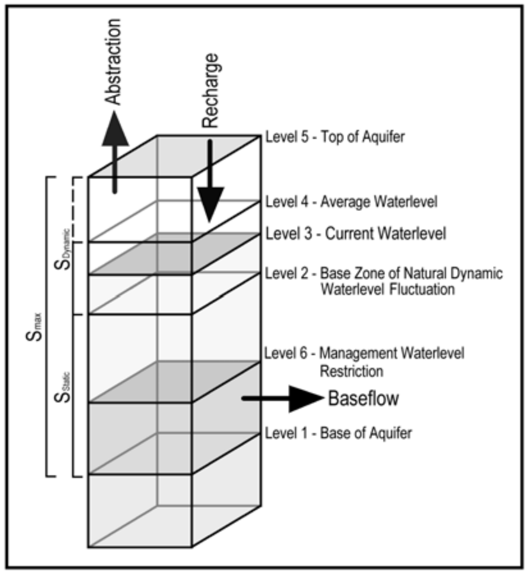

Figure 5: Six Levels in Aquifer System used to assess Volumes of Groundwater held in Storage

The volume of water stored between any two aquifer levels or zones is estimated as the volume of aquifer material reduced by an appropriate storage-coefficient or specific yield. Project 2, which provides the groundwater resource 'planning potential' datasets, makes use of a number of these potential storage volumes together with parameters such as rainfall recharge and baseflow to determine the annual volumes of groundwater available for use on a sustainable basis.

In Project 1 the approach involved defining the thickness and storativity of two aquifer zones, (i) the upper 'weathered-jointed' or WZ and (ii) the underlying 'fractured' zone or FZ. It is estimated that 79% of this water is stored in the WZ which is on average only 33m thick, as opposed to an average FZ thickness of 121m – providing a mean aquifer thickness of 154m. The mean storativity of the WZ and FZ is estimated at $2.62{,}x{,}10^{-3}$ and $1.52{,}x{,}10^{-4}$, respectively. The distribution of storage is shown in Figure 6 which indicates that some 235.5 x 10^9 m^3 of groundwater may be stored in aquifers in South Africa.

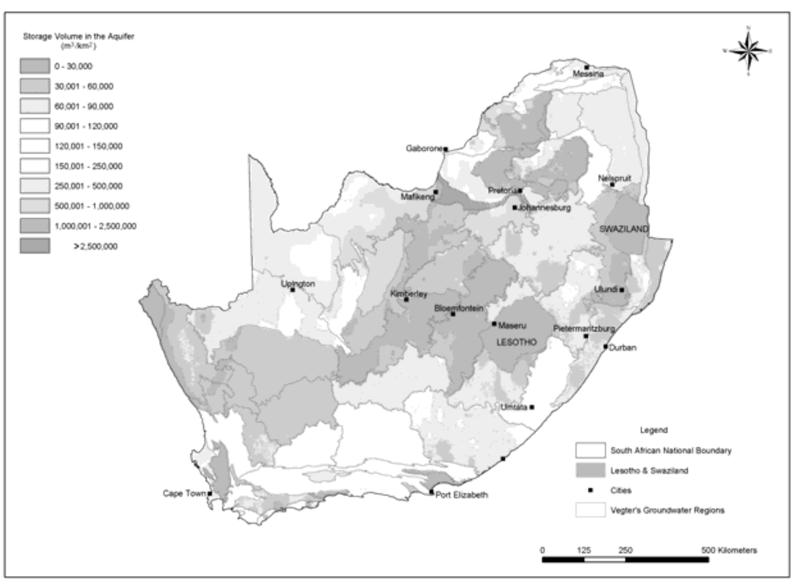

Figure 6: Estimated Total Volume (m^3/km^2) of Groundwater Stored in South African Aquifers

Recharge

Project 3a of GRA2 dealt with groundwater recharge. Chloride mass balance, empirical rainfall/recharge relationships and a GIS based layer model approach were used. This was followed by cross calibration of results with field measurements and detailed catchment studies. A National recharge volume of 30.52 x 10^9 m^3/a was thus calculated.

Exploitable Resource

The exploitable resource is dealt with in some detail here as this is the most important aspect, i.e. how much groundwater can be abstracted under sustainable conditions?

The methodology developed during the GRA2 project employs a basic water-balance approach, where the change in storage in a system is equal to all inputs to, less all outputs from the system.

Over long periods of time and where the groundwater system is in its natural state (i.e. without any abstraction), the natural inputs will be in balance with the natural outputs, such that the change in storage will be zero. This means that the groundwater component of the hydrological system is in steady-state, which implies that the averaged values of the variables have not changed over the time period over which the averaging took place. However, if groundwater is abstracted from the system, this balance is disturbed and the system is no longer in steady-state and water levels will decline in response to withdrawals from groundwater storage. A new steady-state will be established, in theory, if abstraction does not exceed recharge. If abstraction exceeds recharge the system will remain in a dynamic (transient) or unsteady-state. Groundwater is now removed mainly from storage, as well as a proportion from river systems.

A GIS based raster-modelling approach was used to apply these basic water-balance equations to each cell in the study domain for both steady and unsteady-state conditions. The steady-state algorithms are applied, as in the case of the Harvest Potential, to produce information relating the 'average' groundwater conditions using 'averaged' input datasets (i.e. mean annual recharge, average water level etc.) These averaged outputs will only require updating should improved input datasets be acquired or if the algorithm is enhanced. The transient-state algorithms need to be applied at regular time intervals, in this case yearly, to produce outputs about the current status of the groundwater resource, and will be required as input information generated during the previous time step (i.e. antecedent conditions such as aquifer storage and water levels). The algorithms are developed in a hierarchical system whereby the output from one lower-order algorithm is required as input into the next higher-level algorithm, where an additional refinement or management restriction is applied and so on.

The **Groundwater Resource Potential** (GRP) is defined as the maximum volume (m^3) of groundwater that can be abstracted per unit area per annum without causing any long-term 'mining' of the aquifer system (i.e. without continued long-term declining water levels). The GRP is based purely on physical inputs / outputs and aquifer storage. It is therefore not equivalent to the 'sustainable' or 'optimal' yield of the system, which normally takes into account issues such as intrusion of poor quality water, practical and cost issues relating to extracting the water etc. Two basic algorithms have been developed to determine the GRP based on the (i) average or steady-state and (ii) dynamic or transient-state aquifer conditions.

The groundwater resource potential estimates provide a basic indication of the maximum volumes of groundwater that may potentially be abstracted from an aquifer system on a sustainable basis, but there are often many other factors that may restrict or limit the amounts that can actually be abstracted. For example, the exploitation potential assumes that it is possible to establish an equally spaced network of high-yielding production points that are capable of extracting all the groundwater stored within the entire aquifer system, an assumption which is practically impossible. Furthermore, it is physically impossible to abstract all the water stored in an aquifer. Also environmental or legal restraints may be imposed on the volumes of groundwater that may be abstracted, such as legal requirements in terms of the Groundwater Reserve set out in the National Water Act (1998) and environmental requirements of rivers and wetlands in terms of baseflow from aquifers.

Such development and management restraints are imposed on the basic groundwater resource potential estimates to produce a number of derivative datasets, which are described below.

The **Groundwater Resource Potential** datasets are similar to DWAF's Harvest Potential coverage in that they provide estimates of the maximum volumes of groundwater that are potentially available for abstraction on a sustainable basis, and only take into consideration the volumes of water held in aquifer storage and the recharge from rainfall. The feasibility of abstracting this water is limited by many factors due mainly to the physical attributes of a particular aquifer system, economic and/or environmental considerations. One of the most important of these is the inability to establish a network of suitably spaced production boreholes to 'capture' all the available water in an aquifer system or on a more regional scale (Water Systems Management, 2001). The factors limiting the ability to develop such a network of production boreholes, include, *inter alia*, the low permeability or transmissivity of certain aquifer units, accessibility of terrain to drilling rigs, unknown aquifer boundary conditions.

The **Average Groundwater Resource Potential** of aquifers in South Africa is estimated under normal rainfall conditions at 49.249 x 10^9 m^3/a, which decreases to 41.553 x 10^9 m^3/a during a drought. These estimates are regarded as the maximum volumes that could be abstracted on a sustainable basis, if and only if, an adequate and even distribution of production boreholes could be developed over the entire catchment or aquifer system – which is impractical both physically and economically.

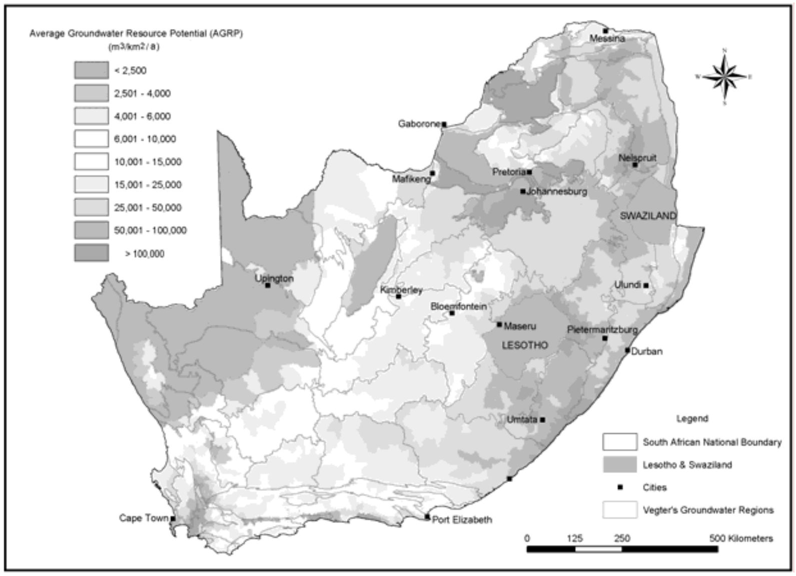

Figure 7: Average Groundwater Resource Potential for South Africa

The GRA2 project made use of Haupt's (2001) concept of an 'Exploitability Factor' and uses Vegter's (1995b) 'Borehole Prospects' coverage to generate an exploitability factor grid for the country. Vegter stated that the prospects of obtaining a groundwater supply from a particular lithological unit may be judged by analysis of the yield distribution of an adequate number of randomly spaced boreholes drilled into this unit. Vegter classified the lithostratigraphic units of the country into 16 water-bearing categories and analysed the yield information from 120,000 boreholes obtained from DWAF's NGDB. The Borehole Prospects coverage is therefore an indication of the extent to which various lithological units are able to act as aquifers. The hard-rock formations of South Africa were subdivided into 18 classes according to the following matrix:

- 6 Exploitability Classes, based upon the probability of obtaining a successful borehole with a yield exceeding 2 l/s. According to Struckmeier (1989) this parameter is a measure of aquifer depth and drilling risk.

- 3 Accessibility Classes – probability of drilling a successful borehole, i.e. a yield exceeding 0.1 l/s. According to Struckmeier (1989) this parameter is a measure of borehole yield and pumping height.

Vegter stated that, given the hydrogeological conditions in South Africa and its limited groundwater resources, the exploitability and accessibility parameters used in his classification are of greater importance than aquifer depth and pumping head.

An Exploitability Factor for South Africa was developed from Vegter's Exploitability – Accessibility GIS dataset, by combining these two parameters into one EF value. This coverage was then converted into a 1km x 1km grid as shown in Figure 7.

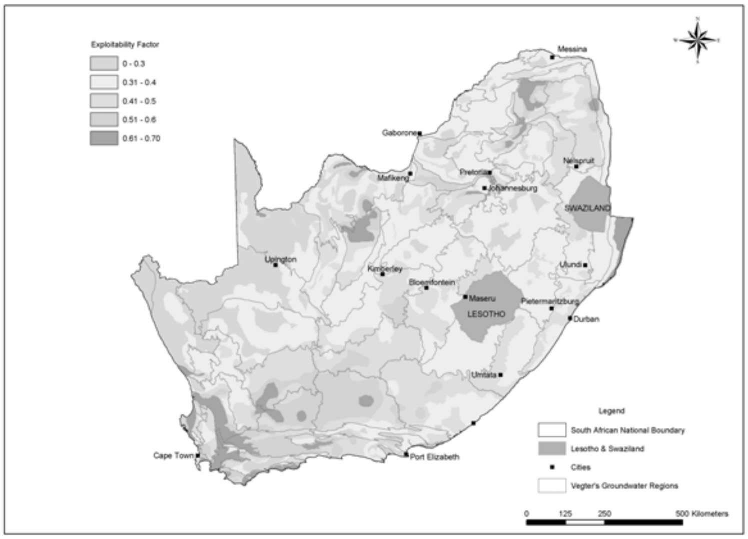

Figure 8: Exploitation Factor for South Africa

The **Average Groundwater Exploitation Potential** of aquifers in South Africa is estimated at 19.073 x 10^9 m^3/a, which declines to 16.253 x 10^9 m^3/a during a drought. It is likely that, with an adequate and even distribution of production boreholes in accessible portions of most catchments or aquifer systems, these volumes of groundwater may be annually abstracted on a sustainable basis.

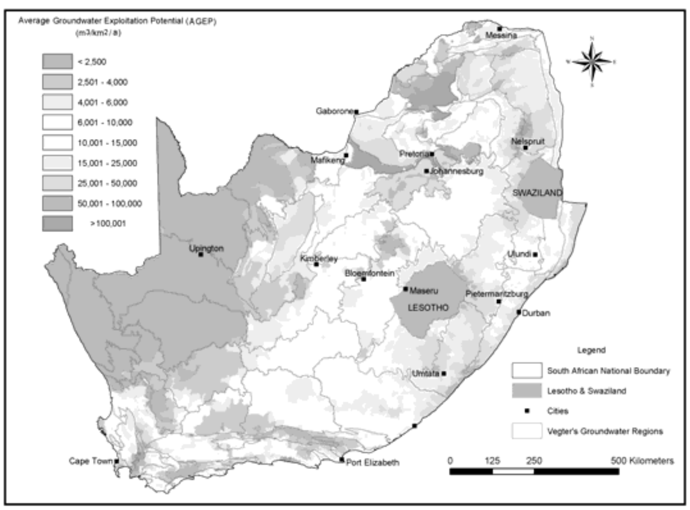

Figure 9: Average Groundwater Exploitation Potential for South Africa

Groundwater quality is one of the main factors restricting the development of available groundwater resources. Although there are numerous problems associated with groundwater quality, some of which are relatively easily remediated, high concentration of Total Dissolved Solids, nitrates and fluoride are considered to be the most common and serious problems associated with water quality on a regional scale.

The **Potable Groundwater Exploitation Potential** of aquifers in South Africa is estimated at 14.802 x 10^9 m^3/a, which declines to 12.626 x 10^9 m^3/a during a drought. Nationally, this represents almost a 30% reduction in the annual volumes of available groundwater for domestic supply due to water quality constraints.

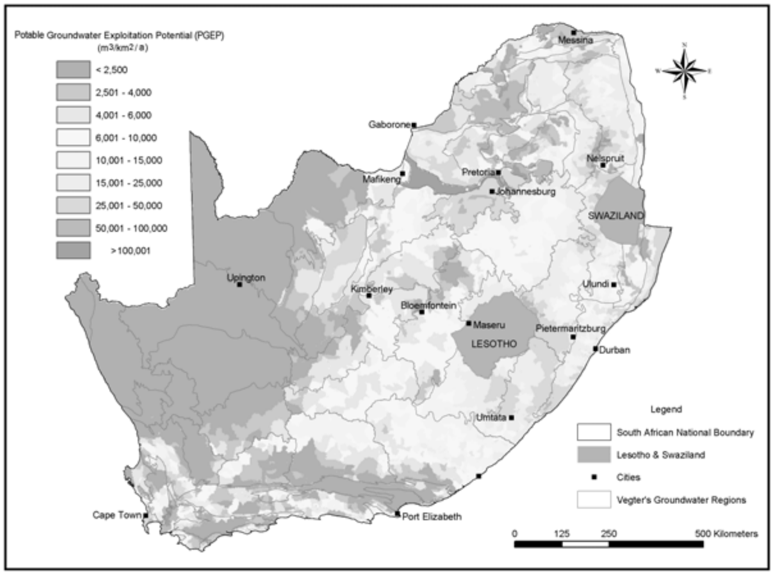

Figure 10: Potable Groundwater Exploitation Potential of South Africa

The volume of water that may be abstracted from a groundwater resource may ultimately be limited by anthropogenic, ecological and/or legislative considerations, which ultimately is a management decision that will reduce the total volume of groundwater available for development – referred to as the Utilisable Groundwater Exploitation Potential (UGEP). This includes the important legislative restriction imposed on the volumes of groundwater available for utilisation by the requirements of the 'Groundwater Component' of the Reserve as stipulated in the National Water Act (1998). Other aspects such as protection against the hazards of saline intrusion or sinkhole formation, conserving important groundwater dependant ecosystems, maintaining baseflow to rivers etc. can all be factored in using this approach.

The **Utilisable Groundwater Exploitation Potential** under normal rainfall conditions and under drought conditions is estimated at 10.353 x 10^9 m^3/a and 7.536 x 10^9 m^3/a, respectively. The UGEP represents a management restriction on the volumes that may be abstracted based on the defined 'maximum allowable water level drawdown' and therefore it is always less than or equal the AGEP. It is likely that, with an adequate and even distribution of production boreholes in accessible portions of most catchments or aquifer systems, these volumes of groundwater may be annually abstracted on a sustainable basis.

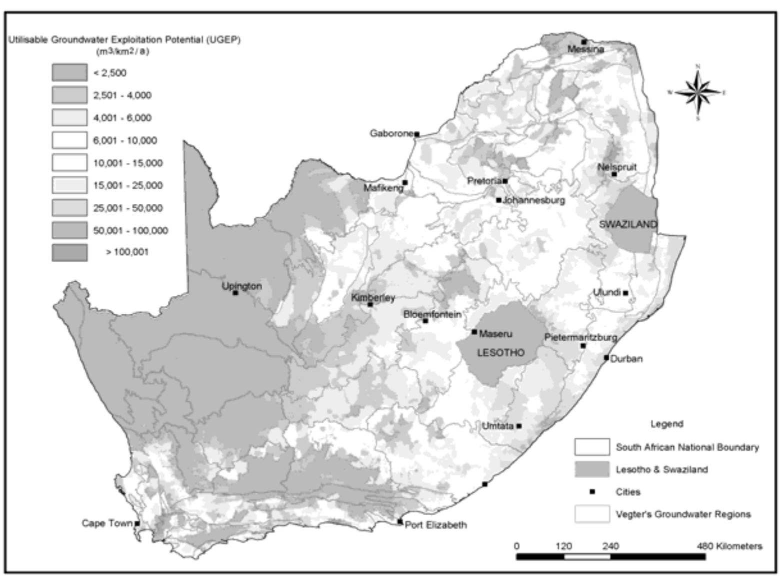

Figure 11: Utilisable Groundwater Exploitation Potential of South Africa

The annual total volume of the Average Groundwater Exploitation Potential (AGEP) is slightly greater than the Harvest Potential or HP, whilst the AGEPDRY is slightly less than the Harvest Potential. The AGRP is more than double the Harvest Potential. When compared to the AGEP, the HP is higher for large parts of South Africa, except in large parts of the Central and Eastern Karoo, as well as Northern Province. During droughts the situation is similar, except that the areas where the HP is greater than the AGEP increases slightly. The HP is significantly greater than the AGEP along the northern Kwazulu-Natal coast, whilst the AGEP is anomalously higher than the HP in groundwater region 10 (Zeerust-Delmas Karst Belt).

6. CONCLUDING REMARKS

Estimates of the available groundwater resource potential of South Africa range from a maximum of 47.727 x 10^9 m^3/a to as low as 7.536 x 10^9 m^3/a. For general planning purposes, it is recommended that the so-called 'Average Groundwater Exploitation Potential' or AGEP be adopted where the total volume of groundwater available for abstraction under normal rainfall conditions is estimated at 19.073 x 10^9 m^3/a, which declines to 16.253 x 10^9 m^3/a during a drought. It is likely that, with an adequate and even distribution of production boreholes in accessible portions of most catchments or aquifer systems, these volumes of groundwater may be annually abstracted on a sustainable basis. Only approximately 6% by volume of the AGEP is currently being abstracted on an annual basis.

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